Astronomical Imaging with the ATA - III

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1. Array configuration

The current design is a 700m diameter array with 350 6m diameter antennas distributed to produce a Gaussian beam pattern with 0.3% sidelobes. Imaging the full field of view of the antennas requires images with ~ 256 x 256 pixels. The naturally weighted synthesized beam has FWHM ~ 75" at 1.4 GHz and ~ 9" at 11.2 GHz for declination 30. With uniform weighting, the corresponding FWHM are 45" and 6" with a factor 2 loss in sensitivity, and ~ 1% sidelobes.

2. Imaging

We considered various imaging procedures. There are two possible routes for producing images: 1) cross correlations followed by gridding and FFT of the uv-data to the sky plane. 2) direct imaging by beam formation over the region of sky of interest. The standard procedure in radio astronomy is to average the cross correlation function from all pairs of antennas. With 350 antennas, this requires 61075 correlations per Nyquist sample time (59 sec). Since this implies a considerable data handling problem, we also considered direct imaging of the full field of view, i.e. averaging the phased array signal for each pixel. This is computationally attractive for a filled array when FFT techniques can be used, but for the current, spare array with the non-regular sampling which is required to give the low sidelobe response, accumulating the correlation function is faster. We still wish to have images as the output, but the computational requirements for imaging from the averaged correlation function is small compared with the correlator, and will be done using general purpose computers. The uv processing steps are calibration, filtering out of bad data, forming the images and deconvolving the instrumental response (the synthesized beam). The low sidelobe response permits that most imaging will NOT require deconvolution, which is often, in radio astronomy, a time consuming, and subjective process. Although the calibration of the data can be automated, the other traditionally subjective and time-consuming step is in editing the uv-data. The speed of the instrument, and the desire to have images as the output requires that this step be automated. We plan to edit the data at several stages through the proposed imaging pipeline. After the frequency part of the correlator, interference spikes will be clipped and flagged in the frequency spectrum in order to preserve the dynamic range in the digitized data. After the cross correlation, the data can again be clipped to remove any strong correlated interference, before storing the averaged correlation functions. At this stage, we will apply amplitude and phase corrections to the data based on calibration sources within the primary beam. The uv-data is then Fourier transformed to form multichannel images of the sky brightness. A simulation using a Sun Ultra 10 workstation produced a 256 x 256 x 256 channel image in 2.5 minutes, so that imaging each Nyquist sample presents no major problem.

Expansion of the Allen Array

We should also consider the impact of possible expansion of the Allen telescope on the back end processing. With more antennas we could fill in the array (more brightness sensitivity) or expand the diameter (more resolution).

An alternative to a correlator is direct beam formation for each pixel. The sampled IF for each antenna is summed with a phase shift appropriate for each pixel, uv sample interval and frequency channel. For a regularly sampled image, the phase shift increment per pixel is constant and need only be computed at each uv-sample interval. This is a similar data rate to the correlator. A possible architecture is a separate processor for each antenna/IF data stream, summing the processed output (phased shifted frequency channels) into a common image matrix.

With a closest antenna spacing twice the antenna diameter, d, to avoid shadowing, the array diameter, D, is given by $\pi/4*D^2 = N\pi d^2$ for a filled circle with N antennas. The sample interval is d/2 to image the full field of view. The size of the 2 dimensional FFT is then $[D/(d/2)]^2 = 16N$ The number of complex multiplies per sample in the FFT direct imaging is then 2*16N*log2(16N) (each loop in the FFT requires 2 complex multiply adds). For an FX correlator the number of complex multiplies per sample is N(N-1)/2.

Some examples:

1) For 500 antennas, direct FFT imaging is faster than an FX correlator if the image size is smaller than 128. The FFT is 1282 * log2(1282) = 229376 (x number of multiplies per loop) The correlator 500*499/2 = 124750 complex multiplies per sample.

2) Even for a filled array with antenna separation twice the antenna diameter, the FX correlator is faster than direct imaging, until the number of antennas is greater than ~1000 if one wants to image the full field of view.

We conclude that building an FX correlator, and imaging the averaged correlation function still makes most sense for an expanded Allen array.

3. Science and Sensitivity

The array is well matched to a number of outstanding observational problems:

Assuming Tsys=40 K, bandwidth=100 MHz with 350 6m antennas, the continuum sensitivity in 1 minute gives an Rms Flux density = 0.25 mJy. The continuum sensitivity is limited by confusion from background sources within the synthesised beam. Kellerman () gives the number of sources with flux density greater than S as, $N(S) = 60\ S^{-1.5}\ Sr^{-1}$; implying that there are on average 1.3 sources brighter than the thermal noise level, 0.25 Jy, in a 1' beam. More recent data (Ref 1) confirm that a compact Allen array will be confusion limited in minutes at 1 GHz, and in hours at 10 GHz. Although the array is confusion limited, it will still be useful for variable sources such as compact extragalactic nuclei and pulsars.

With a wide field of view and excellent sensitivity, the array is ideal for mapping Galactic HI. With 1 kHz resolution (0.2 km/s at 1.4 GHz), the Rms Brightness is 0.4 K in 10 hours at 75" resolution. The whole sky can be imaged with $4\pi/1.6e\text{-}3$ = 7831 pointings without overlap. To adequately sample structures larger than the primary beam, one needs to sample at the Nyquist rate, requiring 31324 pointings for the whole sky. The low sidelobe level of the synthesised beam means that the individual pointings can be combined in a linear mosaic, thus avoiding the considerable complexity of non-linear joint deconvolution techniques (e.g. Cornwell, Sault), and the anguish of years of post processing to remove low level artifacts from surveys (Hartmann, xxxx)

For cold molecular cores in CCS at 11.2 GHz with 0.2 km/s resolution, the Rms Brightness is 0.16 K in 10 hours at 9" resolution.

For Extragalactic HI, a 10 MHz bandwidth gives a velocity coverage of ~ 2,000 km/s. With 256 channels, and a resolution 40 kHz (10 km/s), the Rms Brightness is 50 mK in 10 hours at 75" resolution which corresponds to an HI column density ~ 10^18 cm^-2. With a 100 MHz bandwidth, one would like more channels to preserve the column density sensitivity, which is inversely proportional to sqrt(velocity resolution).

4. Array Calibration.

The array has excellent uv coverage and has a very high data rate, which will rapidly saturate any conventional human data reduction and imaging. The array should produce final, calibrated images as its normal output. Thus the calibration system should leave little room for improvement by post processing, and the uv-data need not be kept for most projects. For the highest image fidelity, it may be necessary to sample the images on a fast time scale to remove residual atmospheric, calibration and interference artifacts.

The calibration of the array will proceed in an iterative fashion. Calibration of the delays for each antenna is obtained from the slopes across the 100 MHz bandpass. The antenna phases can then be obtained by observing unresolved sources and fitting the phases. N(N-1)/s baselines are used to fit N-1 antenna phases; there are (N-1)(N-2)/2 independent data points.

The continuum sensitivity in 100 MHz is 0.25 mJy in the Nyquist sample time of 1 minute for the whole array. To determine the phase of each antenna we effectively phase up N-1 antennas and correlate versus the unknown antenna to determine its phase. The sensitivity is then 5 mJy per antenna.

Amplitude and phase errors

We investigated the effect of amplitude and phase errors on the synthesized beam response.

i.) Phase errors

Phase errors	Peak amplitude	RMS sidelobe
0	1.00	3.04 e-3
5	0.99	3.05 e-3
10	0.98	3.07 e-3
20	0.87	3.17 e-3
50	0.48	3.66 e-3

ii) Amplitude errors

Amplitude error(%)	Peak amplitude	RMS sidelobe
0	1.00	3.04 e-3
10	1.01	3.10 e-3
20	1.03	3.23 e-3
50	1.08	4.12 e-3

A 5 degree phase and 10% amplitude error with 3.14 e-3 RMS sidelobes, or a 5 degree phase and 15% amplitude error with 3.17 e-3 RMS sidelobes are acceptable levels of degradation. Another way of looking at this is 5 degrees is only 1/72 wavelengths. There are a sufficient number of calibration sources within the primary beam to achieve this without re-pointing the antennas away from the target source.

A 5 degree phase error requires a SNR of ~10, which, per antenna, requires a 50 mJy source with a 1 minute integration. Kellerman gives N(S) = 60 S-1.5 Sr-1; implying, on average, about 8 sources brighter than 50 mJy within the 136' primary beam at 1.4 GHz with a field of view 1.6 e-3 Sr.

5. Image Formation and Self-Calibration

The high data rate lends support to the idea of forming images, and not storing correlation data. One can still make an image of the instrumental response (the synthesized beam) and deconvolve the images when needed. The images can be written out at some reasonable data rate for evolving sources such as comets. Not storing correlation data precludes the conventional self-calibration. However, the tropospheric path fluctuation at cm wavelengths is around 1 mm on a 1 km baseline in 5 min. This is only 1/30 wavelength at 10 GHz and is probably not limiting the image quality. At wavelengths longer than about 30 cm, fluctuations in the ionosphere may limit the resolution. The calibration system should measure the tropospheric and ionospheric delays for each sample interval using strong point sources within the field, and apply the phase corrections to the data streams from each antenna before the data feeds into the imaging, or beam forming hardware. If the calibration system uses the same frequency as the observations, then the measured delay (tropospheric + ionospheric) is appropriate for the observations. If the calibration is done at a widely different frequency, it may be necessary to solve for the tropospheric and ionospheric delays. This can be done if the calibration data contain simultaneous observations of centimeter and decimeter wavelengths. To further complicate long wavelengths, the primary beam size could be larger than the isoplanatic angle - the coherence scale of the ionosphere. In this case it may be necessary to observe multiple calibrators within the primary beam in order to determine the appropriate calibration across the field of view. This correction can be applied to the correlation data for each sub-field.

References.

1. Bower, 6 Oct 2000, ATA memo series.
2. Kellerman
3. Cornwell, T.J., 1989, Synthesis Imaging in Radio Astronomy. Ed. R.A. Perley, F.R. Schwab, \& A.H.Bridle, ASP Conf. Ser. 6, 277
4. Sault, R.J., Staveley-Smith, L. \& Brouw, W.N. 1996, A\&A Supp., 120, 375
5. Hartmann,